Continental Fog Attenuation Empirical Relationship from Measured Visibility Data

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Abstract. *Free Space Optics (FSO) has the great potential for future communication applications. However, weather influenced reduced availability had been the main cause for its restricted growth. Among different weather influences fog plays the major role. A new model generalized for all FSO wavelengths, has been proposed for the prediction of continental fog attenuation using visibility data. The performance of the proposed model has been compared with well known models for measured attenuation data of continental fog. The comparison has been performed in terms of Root Mean Square Error (RMSE).*

Keywords

FSO, attenuation, simulation, fog, model comparison.

1. Introduction

The rising need of wireless broadband communication links has instigated the interest in Free Space Optical Communication technology. The high carrier frequency of FSO in the range of 20 THz to 375 THz, renders it to provide high data rates. License free communication, easy installation, avoiding electromagnetic pollution and wiretapping safety are among other advantages. Delay free web browsing and data library access, electronic commerce, streaming audio and video, video on demand, video teleconferencing, real time medical imaging transfer, enterprise networking, work-sharing capabilities and high speed interplanetary internet links are different foreseen implementations [1]. Different FSO implementation scenarios recently under research are ground-to-ground (short and long distance LOS terrestrial links), satellite uplink/downlink, intersatellite, satellite or deep space probes to ground, ground-to-air (e.g., UAV, HAP etc.)/air-to-ground terminal. Some successful experiments have been carried out like SILEX (Semiconductor intersatellite link), the link between OGS and ARTEMIS (Advanced Relay Technology Mission Satellite) and the earth reconnaissance low earth orbit (LEO) satellite SPOT-4.

However, a reliable operation and a certain availability of the link is the basic requirement of any application. The propagation channel influences the transmission in any communication system. The propagation channel for FSO is atmosphere and FSO links are mainly affected by the local weather. Fog is the most detrimental attenuation factor among all atmospheric attenuating factors of FSO. Fog attenuation measurement campaigns have shown that attenuation has peak values of 480 dB/km under dense fog [2]. The prediction of fog attenuation can be helpful for analyzing the performance of FSO links. The most accurate but complex calculation of attenuation for fog droplets is based on Mie scattering theory. However, it requires detailed information of fog parameters like particle size, refractive index, particle size distribution etc. This information may not be readily available at a particular location of installation.

The alternate way to predict specific attenuation is by using visibility data. There are models like Kruse, Kim and Al Naboulsi that predict specific attenuation in terms of visibility. However, when the predicted value by any model is compared with measured continental fog attenuation data, the measured attenuation data does not seem to follow any particular model predicted attenuation. The new model was proposed in [3] for dense maritime fog. That model used the same measurement data for performance comparison which was used for modeling. Moreover the model was specific for only two wavelengths of 850 nm and 950 nm. In this paper a new model has been proposed for continental fog which is generalized for all wavelengths used for FSO. The measured attenuation and predicted attenuation by new model and existing models have been compared in terms of RMSE using the measurement data that has not been used for modeling.

The remainder of this paper has been organized as follows: Section 2 presents the fog model predicting specific attenuation in terms of visibility. Simulations for existing models are presented in section 3. Section 4 presents the new proposed model and comparison of different models for fog events. Concluding remarks finalize this paper in section 5.

2. Fog Models Predicting Specific Attenuation in Term of Visibility

The fog was analyzed as the most destructive factor producing huge signal attenuation for considerable amount of time. The models Kruse, Kim and Al Naboulsi [4 - 7], predict fog specific attenuation using visibility. The visibility is defined as the distance to an object where the image distinction drops to 2 % of what it would be if the object were nearby instead. Image distinction drop to 5% is also considered for visibility definition. The visibility is measured at 550 nm, the wavelength corresponding to the maximum intensity of the solar spectrum. Visibility measured according to this definition at meteorological stations or airports is the only parameter describing fog, available for many locations worldwide, in contrast to more specific parameters such as drop size distribution or liquid water content required for Mie scattering theory. The specific attenuation in dB/km for both Kim and Kruse model is given by [4]

$$att_{spec-Kim\&Kruse} = \frac{13}{V(\mathrm{km})}\left(\frac{\lambda}{\lambda_0}\right)^{-q} . \qquad (1)$$

Here *V(km)* represents visibility, λ in nm stands for wavelength and λ_0 as visibility reference wavelength (550 nm). For Kruse model [5].

$$q = \begin{cases} 1.6 & \text{if } V > 50\,\text{km}, \\ 1.3 & \text{if } 6\,\text{km} < V < 50\,\text{km}, \\ 0.585 V^{1/3} & \text{if } V < 6\,\text{km}. \end{cases} \qquad (2)$$

Equation (2) implies that for any meteorological condition, there will be less attenuation for higher wavelengths. The attenuation of 10 μm is expected to be less than attenuation of shorter wavelengths. Kim rejected such wavelength dependent attenuation for low visibility in dense fog. The q variable in (1) for Kim model [6] is given by

$$q = \begin{cases} 1.6 & \text{if V} > 50\text{ km} \\ 1.3 & \text{if 6 km} < \text{V} < 50\text{ km} \\ 0.16\text{ V}+0.34 & \text{if 1 km} < \text{V} < 6\text{ km} \\ \text{V} - 0.5 & \text{if 0.5 km} < \text{V} < 1\text{ km} \\ 0 & \text{if V} < 0.5\text{ km} \end{cases} \qquad (3)$$

Al Naboulsi et al. (France Telecom model) [7], [8] has provided relations to predict fog attenuation by characterizing advection and radiation fog separately. The advection fog is formed by the movements of wet and warm air masses above the colder maritime and terrestrial surfaces. Al Naboulsi provides the advection fog attenuation coefficients as

$$\gamma_{ADV}(\lambda) = \frac{0.11478\lambda + 3.8367}{V} . \qquad (4)$$

Radiation fog is related to the ground cooling by radiation. Al Naboulsi provides the radiation fog attenuation coefficients as

$$\gamma_{RAD}(\lambda) = \frac{0.18126\lambda^2 + 0.13709\lambda + 3.7502}{V} . \qquad (5)$$

In (4) and (5), λ is in nm and V is in km. The specific attenuation in dB/km for both types of fog is given by Al Naboulsi as follows

$$att_{spec-AlNaboulsi} = \frac{10}{\ln(10)}\gamma(\lambda) . \qquad (6)$$

In this paper the comparison of these models is done in terms of root mean square error from the measured experimental data for continental maritime fog.

3. Measurement, Simulation and Results

The specific attenuation in dB/km at 830 nm on 100 m path and the specific attenuation at 1550 nm on the parallel 100 m path were measured concurrently at the Czech Metrological Institute for in 2009. Weather observation system at the receiver end uses Vaisala PWD11 device for visibility range measurements. Simulations were performed to compare the measured value of fog FSO specific attenuation under continental fog conditions and attenuation predicted by different models. Fig. 1 shows this comparison but from Fig. 1 it cannot be inferred that which model performs better than others. Although Al Naboulsi model seems to be closer to the measurement data but still it cannot be said certainly that this model is better.

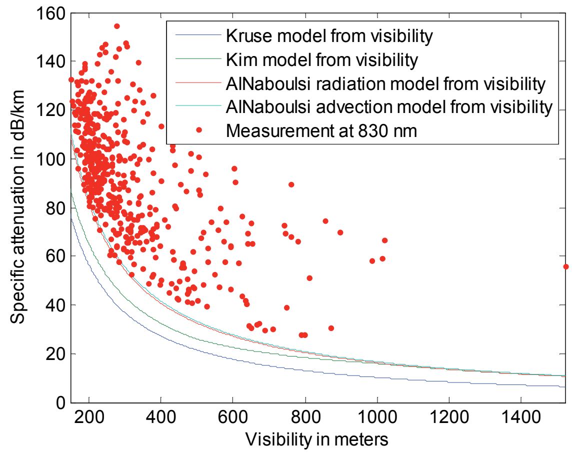

Fig. 1. Measured attenuation for 830 nm and fog attenuation predicted by different models.

Fig. 2 shows the magnified view up to 300 m. Again Al Naboulsi models seem to be better but the magnified view even cannot help in the determination of the best model.

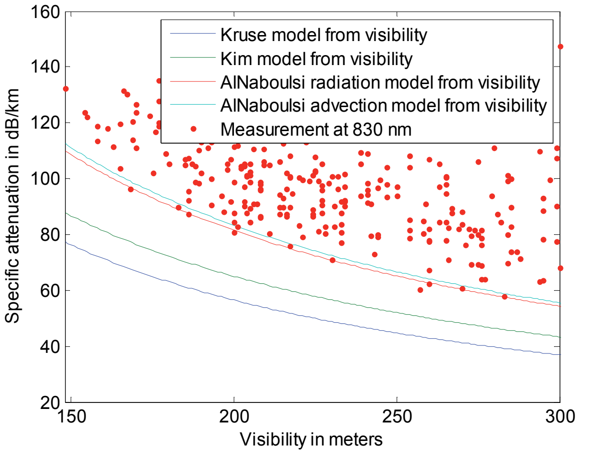

Fig. 2. Magnified view of comparing different models for measured attenuation data for 830 nm.

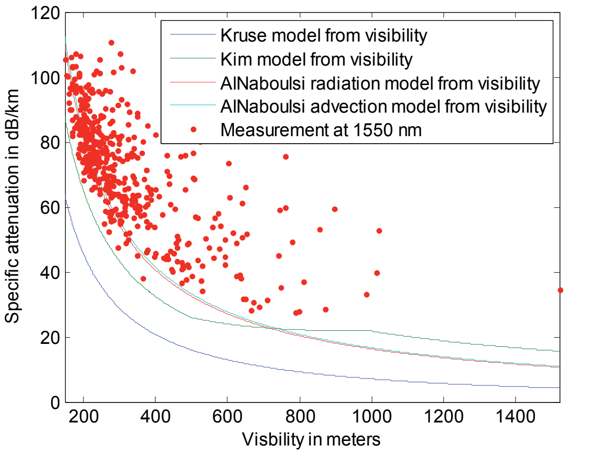

Fig. 3. Measured attenuation for 1550 nm and fog attenuation predicted by different models.

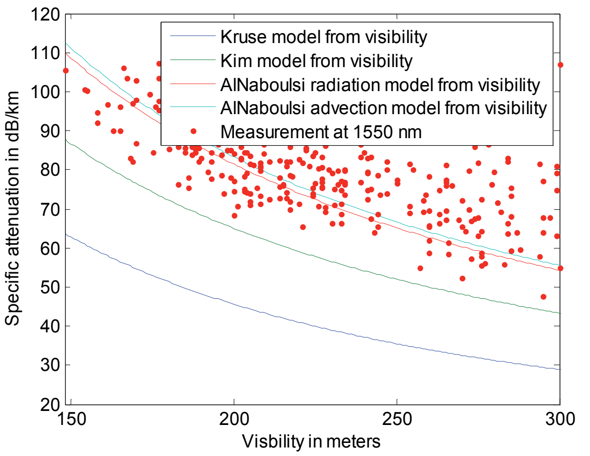

Fig. 4. Magnified view of comparing different models for measured attenuation data for 1550 nm.

The same simulations were performed for 1550 nm wavelength. Fig. 3 shows the measured specific attenuation and specific attenuation predicted by different models. It can be observed that specific attenuation of 1550 nm is quite low in comparison to 830 nm. However, none of the model seems to be better. The magnified view is presented in Fig. 4. But the magnified view also does not help in supporting any model over others.

4. New Proposed Model for Continental Fog and Comparison of RMSE

The results of the previous section show that any existing model cannot be preferred. It poses the need of a new model that can provide better prediction of attenuation in terms of visibility.

A new model is proposed here that has the least RMSE. The model is given as follows for 830 nm wavelength. If $att_{spec\text{-}proposed}$ is the specific attenuation in dB/km and V is the visibility in meters,

$$att_{spec-proposed} = a.e^{b.V} + c.e^{d.V}\,. \tag{7}$$

Coefficients (with 95% confidence bounds):
a = 142.5 (114, 171.1),
b = -0.004006 (-0.006492, -0.001521),
c = 40.94 (-3.121, 85),
d = 0.0002315 (-0.0007919, 0.001255).

Goodness of fit:
SSE: 1.697e+005,
R-square: 0.4417,
RMSE: 18.88.

If M_att and P_att are measured and predicted specific attenuation by proposed model respectively and n is the total number of measurements, the (SSE) sum of square error is calculated as follows

$$SSE = \sum \left(M\_att - P\_att\right)^2\,. \tag{8}$$

The root mean square error (*RMSE*) is given as follows

$$RMSE = \sqrt{\frac{SSE}{n}}\,. \tag{9}$$

If μ is the mean of M_att, *R-square* is given as follows [9]

$$R - square = 1 - \frac{SSE}{\sum\left(M\_att - \mu\right)^2}\,. \tag{10}$$

The curve fitting by this model is given as follows.

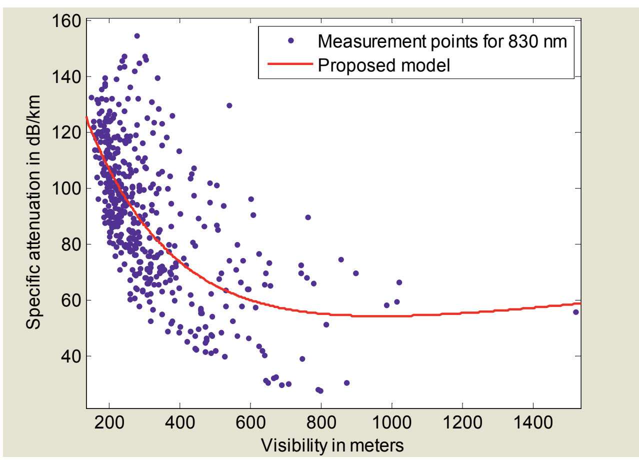

Fig. 5. Curve fitting by the proposed model for measured specific attenuation at 830 nm wavelength.

Similarly the model proposed for1550 nm wavelength is given as follows.

$$att_{spec-proposed} = a.e^{b.V} + c.e^{d.V} . \quad (11)$$

Coefficients (with 95% confidence bounds):
a = 104.9 (81.79, 128.1),
b = -0.005618 (-0.009053, -0.002183),
c = 54.4 (23.13, 85.67),
d = -0.000302 (-0.0009613, 0.0003572).

Goodness of fit:
SSE: 5.765e+004,
R-square: 0.5933,
RMSE: 11.01.

The curve fitting for this model is given as follows:

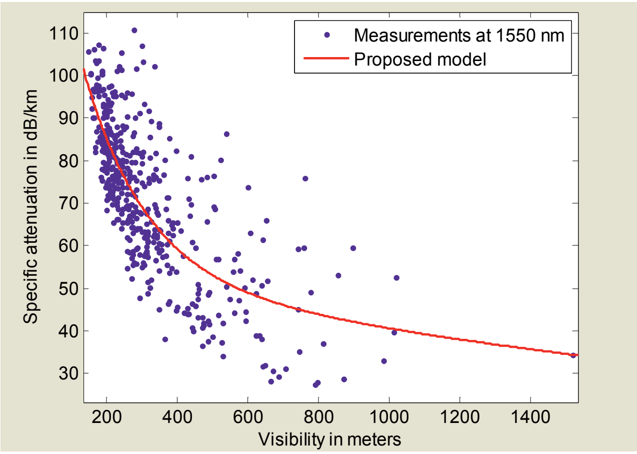

Fig. 6. Curve fitting by the proposed model for measured specific attenuation at 1550 nm wavelength.

So the generalized expression of specific attenuation $att_{spec\text{-}proposed}$ in terms of visibility V is given as follows

$$att_{spec\_proposed} = a.e^{b.V} + c.e^{d.V} . \quad (12)$$

The expressions for a, b, c and d in terms of wavelength λ in nm are given as follows

$$a(\lambda)= 185.8 - 0.0522\ \lambda, \quad (13)$$

$$b(\lambda)= -2.239\cdot10^{-6} - 0.002148\ \lambda \quad ,(14)$$

$$c(\lambda)= 25.42+ 0.01869\ \lambda, \quad (15)$$

$$d(\lambda)= 0.0008465 -7.41\cdot10^{-7}\ \lambda. \quad (16)$$

The root mean square error of 830 nm is shown in vertical axis of Fig. 7. The root mean square error of 1550 nm is shown in vertical axis of Fig. 8. Fig. 7 and Fig. 8 show the difference between the proposed model RMSE and the RMSE by other models. As RMSE is considered as metric for comparison, it shows that the proposed model performs better than the previous works.

As per expectation, the performance of the proposed model is better than other models for this fog measurement data because the proposed model has been modeled using the same measurement. The performance of the model is also compared for another fog measurement of January 2009. Fig. 9 shows the performance comparison of 830 nm.

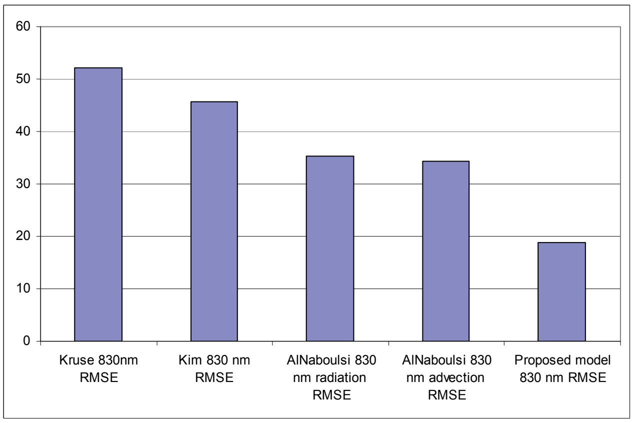

Fig. 7. Root Mean Square Error of different models for 830 nm data.

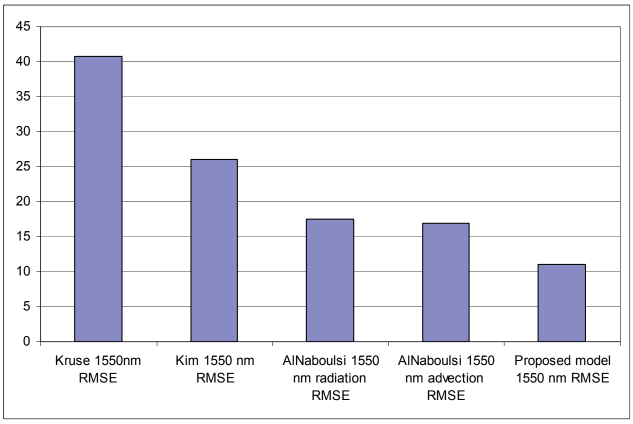

Fig. 8. Root Mean Square Error of different models for 1550 nm data.

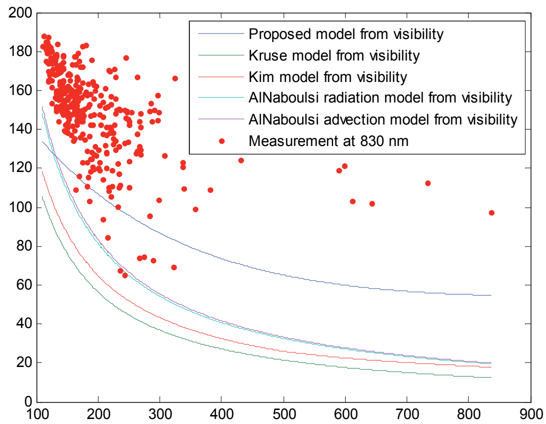

Fig. 9. Measured and predicted specific attenuation by different models of 830 nm for January 2009 fog event.

The vertical axis of Fig. 10 shows the Root Mean Square Error (RMSE) of different models. As the proposed model has the least RMSE, it is obvious that the proposed model performs better even for the measurement data which has not been used for its modeling.

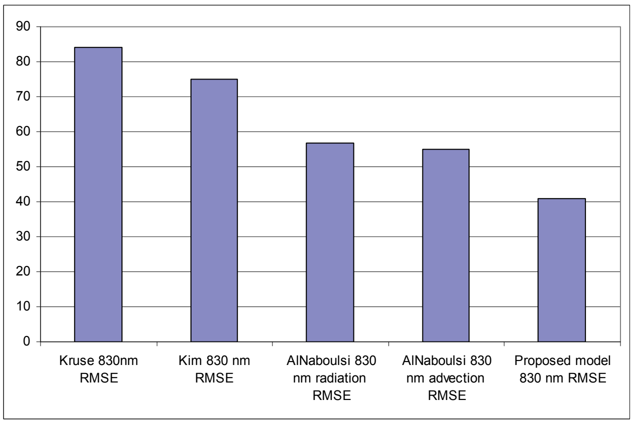

Fig. 10. Root Mean Square Error of different models for 830 nm data of January 2009.

Fig. 11 shows the attenuation predicted by different models and measured attenuation. The vertical axis of Fig. 12 shows the root mean square error comparison of different models for 1550 nm measurement data of January 2009. Again it can be observed that the proposed model is performing better. These results show that the proposed model supersedes other models even when it is compared for the other measurements.

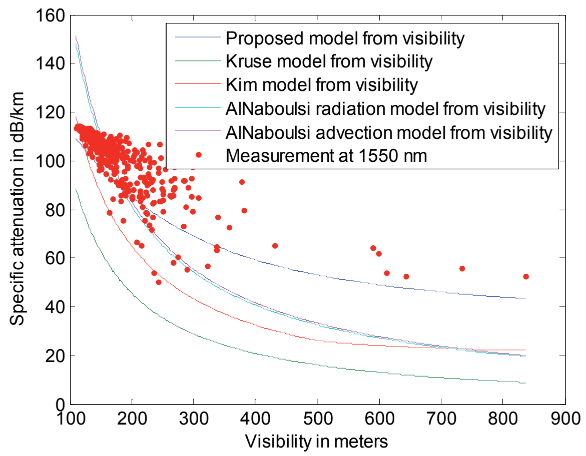

Fig. 11. Measured and predicted specific attenuation by different models of 1550 nm for January 2009 fog event.

5. Conclusion

A new model has been proposed using measured attenuation and visibility data for continental fog. The comparison of existing models and the new model in terms of RMSE for this measurement data shows that this new model predicts more accurate than other models. However, as this measurement data is the same for which the model has been formulated, the performance of this model is expected to be better than others. The countercheck has been performed by comparing models using other measurement data of visibility and attenuation. This comparison also supports the new model showing that its performance is better than other models. This comparison exhibits the accuracy of the proposed model and advocates for its use.

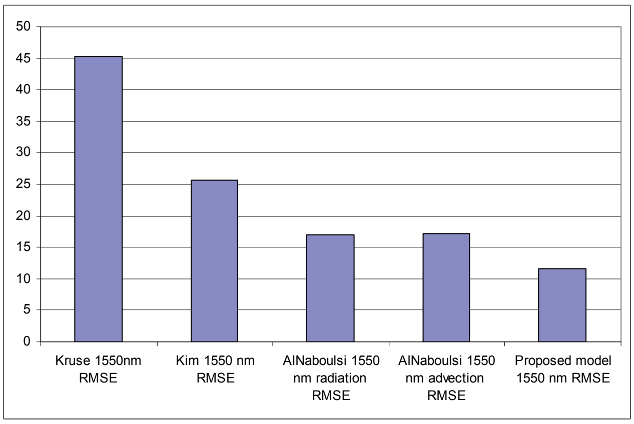

Fig. 12. Root Mean Square Error of different models for 1550 nm data of January 2009.

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